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ORIGINAL PAPER

Analogy Between Quantum and Cell Relations

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Abstract Relations occur on all levels of systems. Following a major assumption of generalized quantum theory, namely that the principles of quantum mechanics will occur on higher system levels as well, it was investigated in an a posteriori analysis of pre-existing data whether relational patterns found for two-photon experiments are similarly performed by two cell-populations. In particular, the typical pattern in outcomes of two-photon entanglement experiments was extrapolated to discover similar patterns of relationships in the cellular biological system of the Ciliate *Paramecium caudatum*. In the former case we find one photon assuming a particular state when being measured and the other assuming a correlated state with regard to the first particle. From a perspective of degrees of freedom (*df*) the author interprets this outcome as follows: Each particle has only one *df* for assuming a particular state (e.g. its spin). When measured this is leading to a pattern: They use their two degrees of freedom for establishing a relation among them (particle-to-particle) and for a relation with the environment (particle-to-measurement). If this pattern is unique then we should find it also in cell-to-cell relationships. It was suggested to consider causations in cell-to-cell relations as the analogue to the relationship between the quantum particles (see above) and the dependence of repeating the experiments as the analogue to the measurement event in the quantum experiment. It was hypothesized that in a relational system of two cell populations only one should be sensitive to the repetition of the experiment. The other population, however, should establish a relation with the first one. Since the author had successfully performed experiments with pairs of cell populations that were separated with glass barriers from each other but having effects on each other (Fels in PLoS One 4:e5086, 2009), the system was perfectly well suited for testing the hypothesis. The assessed cell variable was cell division. An a posteriori analysis

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of three similar experiments confirmed that when populations were in a relation with each other, only one of them stood in relation with the repetition of the experiment.

Keywords *Paramecium caudatum* · Degree of freedom · Cell growth · Communication · System level

1 Introduction

Nothing is without relation. For example, in an entanglement experiment with two quanta (photons) that are measured along the same axis, we make typically two observations: First, measuring the spin of one photon, that photon is relating to the measurement and assumes a spin, while second, the other photon relates to the first photon assuming a correlated spin—even though it perceives no signal from that first photon (Ananthaswamy 2003; Aspect et al. 1982). Such non-causal relationships were originally described for purely physical devices where measurements were taken of two quanta (photons) and their particular states (polarization angle or spin) (Ananthaswamy 2003; Aspect et al. 1982). But entanglement … *being one of the most profound features of quantum mechanics* … is not reduced to non-causally correlated states of two particles: it includes macroscopic objects, such as atomic gases, too (Julsgaard et al. 2001). Furthermore, it has been shown that theoretically the principle of entanglement can be generalized to other systems, e.g. biological and social systems (von Lucadou et al. 2007). But when we look at, e.g. biological systems, the number of quanta potentially involved in causal or non-causal relationships can neither be quantified nor localised, which implies that we cannot develop an experiment where we control for all variables and hence, predictability of finding quantum-based correlations is limited (compare with Atmanspacher et al. 2002). Nonetheless, comparing the macroscopic with the microscopic dimension had led to the formulation of the *generalized quantum theory* whose major notion is … *that certain principles, in particular probability, observables, complementarity and entanglement, can be applied not only to* […] *quantum systems but to systems in general* (von Stillfried 2010). Von Stillfried (2010) distinguishes in this context between the reductionist position, namely that all matter has quantum properties to some degree because it consists of quanta, and the system theoretical position, claiming that entanglement and other phenomena described by quantum theory are actually system-inherent principles (for references read von Stillfried 2010). Positioned on that systems theoretical perspective, the author hypothesizes that such system-inherent principles might include also patterns of relations assumed by observables. Accordingly, this study looks for analogies in relational patterns comparing entangled systems of two-quanta with systems of two mutually exposed cell populations belonging to the aquatic, unicellular organism *Paramecium caudatum* (Cilliata) (see Fels 2009). The study refers to data that were published in another context (Fels 2009) and to yet unpublished data. In either case the analysis was performed a posteriori—evoked after carefully reading and then reinterpreting the outcome of typical two-photon entanglement experiments.

Again, a simplified description of the outcome of a typical two-photon entanglement experiment is this: When being measured, one photon assumes a particular state (spin) and the other assumes a correlated state (spin) with regard to the first photon. Note, a two-photon experiment belongs to the smallest samples of objects which we can see in its relations under otherwise fully controlled conditions. Further, even though photons that propagate in opposed directions cannot perform causal effects on each other, they anyway do relate to each other—with this evidently only remaining option of being non-causally related, which is called entanglement. However, here we have the relational pattern of such a typical quantum entanglement experiment with two particles in focus. We, furthermore, interpret that pattern using the term *degree of freedom* (*df*). Given the capacity and regarding a particular characteristic—such as e.g. spin or cell growth—we define here this degree of freedom as the freedom of an object to relate with another object or (physical) condition. This leaves an object with only one such degree of freedom to relate with. Hence, when a photon assumes a spin, it has used its degree of freedom of doing so. In addition, for the case of the entangled photons, we can say that when each photon uses its degree of freedom for assuming a spin, they together establish a pattern: One *df* goes to a relation among them (particle-to-particle) and one *df* goes to a relation with the environment (particle-to-measurement). This, however, leads to the working hypothesis of this study, formulated here as the very general description of two relating observables, namely that one observable uses its *df* for an external (the measurement) and the other for an internal relation (with the first observable) (confer Fig. 1).

With the above-mentioned general description of a relational pattern performed by a system of two objects we will look now at a particular experimental arrangement of two groups of cells that were separated by quartz or normal glass from each other (Fels 2009). The original question, namely whether two groups of cells would cause effects on each other's growth through glass and this probably due to endogenous photons, was confirmed for a set of experiments (see Fels 2009) (note that these photons are considered purely as signals, hence leading to causal relations). However, at that time it was not analysed whether the two groups used their degrees of freedom in the above sense, having in mind the characteristic *cell division*. Note also, even though the internal relation is for the above-described two quanta system a non-causal relation, changing the system level to cells does not

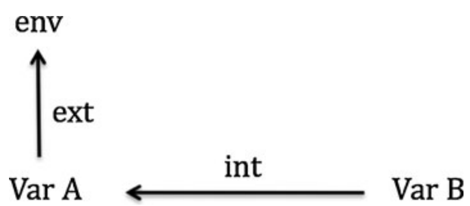


Fig. 1 This figure represents a scheme displaying two variables (var A and var B) and their internal and external relation. The *arrows* indicate the use of the two degrees of freedom (confer text) of both variables: one for the internal relation (int; being local or non-local) of one variable (B) with the other (A) and one for the external relation (ext) of that other variable (A) with the environment (env)

imply that the internal relation has to be non-causal; it can as well be a causal relation simply because in biological systems there are more options of relating to each other, e.g. chemically or electromagnetically, than in a two quanta system (where only two photons propagate in opposed directions at a speed of c).

But what is an external relation in a biological system? Within biological systems, keeping experiments as standardised as possible, their repetition contributes tremendously to variation in variables (e.g. in experiments on effects of food concentrations on infection probability, the strongest effect explaining variation in the data came from the repetition of the experiment Fels 2005). In other words, repeating an experiment several times (for reasons of statistical reliability at least five times) we can easily detect whether a group of cells relates to the (physical) environment or not. Even though this does not explain what exactly the cell (or any organism) is relating with (in its environment), there is evidence that e.g. cells, can relate to an electromagnetic environmental factor: It was shown for single groups of cells (including *Paramecia*) that the amount of natural background radiation had a significant effect on cell growth (Kozlov 2000). We could also say that these single groups of cells gave their (one) degree of freedom for assuming a particular number of cells in relation with an external factor, here background radiation. To conclude, repeating several times an experiment with two populations of cells that can have effects on each other allows a simultaneous detection of effects between two groups of cells and between cells and an (unknown) environmental factor. The goal of this study was to see whether only one of two otherwise related groups of cells would relate to an external factor. A positive answer allows stating those two quanta in an entanglement experiment, on the one hand, and those two groups of cells in an ecological experiment, on the other hand, display the same relational pattern.

In an a posteriori analysis of data obtained from studies with *Paramecium caudatum*, it was found for two different experiments that while groups significantly related with each other, only one of them related with the environment. In one experiment, no relation between the groups could be distinguished and furthermore, both related with the environment. Note, groups of cells that were kept singly, all related strongly with the environment. The findings are discussed in relation to system formation as well as to entanglement in higher system levels.

2 Materials and Method

2.1 Study Organism

The study system is the unicellular aquatic organism *Paramecium caudatum* (Ciliata). Paramecia are big cells (0.2–0.3 mm in length), therefore easy to count with the help of a binocular magnifying glass. They are maintained in 50 ml (Falconer) tubes at temperatures from 23 to 27°C, which is an optimal temperature range regarding cell division (Wichtermann 1986). Once per week they are fed with Medium containing bacteria, their source of energy (for more details refer Fels and Kaltz 2006).

2.2 Cuvettes

Cuvettes are used in order to separate populations chemically but not optically from each other by placing small (inner) cuvettes into big (outer) cuvettes (together referred to as units). The cuvettes are made of (normal) glass or quartz (glass) influencing the outcome of mutual exposure (Fels 2009): Those of glass allow transmission of photons up to frequencies in the range of UV-A (thus having the property of being a filter for photons in the range of UV-C and UV-B) while quartz cuvettes—not being UV filters—allow the transmission of photons up to the range of UV-C (for more details read Fels 2009, and references therein).

2.3 Mutual Exposure of Cell Populations

At the beginning of an experiment, cells were always taken from one mother-tube. For reasons of counting—with the help of a binocular magnifying glass—cells were placed on flat wells and individually separated with a 20 μl-pipette. Finally, 1 ml of medium was put into each of the cuvettes as well as a defined number of cells; in the controls the units had only one cuvette containing a cell population. After placing the two populations into a small and a big cuvette, respectively, the (cuvette) units were randomly placed in a grid and kept under total darkness for 48 hrs in a black box. During this mutual exposure time, the populations grew, i.e. the cells were dividing. At the end of replicating an experimental block, the cells were counted and then removed, i.e. they never became part of a next repetition of the experiment.

2.4 External and Internal Cell Relations

The external relation refers to an (unknown) environmental factor assumed to alter with time. It is best discovered as a variation in cell division rates being due to repeating the experiment. For reasons of reliability into statistical analysis of the results, such an experiment should be repeated at least five times.

The internal relations of the cells of *Paramecium caudatum* are (so far) known to have qualitative effects such as (1) increasing or (2) decreasing cell division in the neighbouring population (Fels 2009). These relations, depending on separating material (quartz or glass) and population size are considered as causal relations—most probably due to electromagnetic signals, i.e. photons (Fels 2009).

2.5 Experiments 1a (Quartz Separation) and 1b (Glass Separation)

The original experiment (Fels 2009) tested for the effect of small populations of inducer cells (5 cells), placed in the inner cuvette, on growth of bigger populations of tester cells (25 cells), placed in the outer cuvettes when separated by quartz or glass. In order to test for neighbour effects in these units there were also populations without a neighbour, namely controls with 25 cells at the beginning of an experiment. The exact details of this experiment and its main results with regard to signalling effects on cell growth are described elsewhere (Fels 2009). The original question focused on assumed effects of photons exchanged between populations:

Using two separating materials was part of one hypothesis and hence, of one experiment. However, in this a posteriori analysis the focus is on relational patterns of two cell populations and since separating them either with quartz or with glass had led to two subsets producing different results, they are presented like two experiments, namely 1a and 1b. However, note, that 1a and 1b were simultaneously performed, i.e. being part of the same experimental blocks.

Here, we revisit the results but refer to the use of the degrees of freedom with a special focus on the external relation. Each experimental block—containing five units of separated populations and five controls for each, 1a and 1b—was repeated five times (within 5 weeks) thus satisfying minimal requirements for statistical analysis of effects on cells due to the repetition of the experiment, hence, detecting cell-to-environment relations.

2.6 Experiment 2

This experiment tested for the relation of big populations of (inducer) cells (100–140 cells), placed in the outer cuvette, on small populations of (tester) cells (5 or 6 cells), placed in the inner cuvettes. This author's first experiment on mutual influence of cells with quartz separation was looking for growth correlations between inner and outer populations. In order to find such effects there were 10 (once 19) replicates of units per experiment. Each block was seven times repeated, three times at the CNRS (Université Pierre et Marie Curie, Paris 6, France) and four times at the Swiss Tropical and Public Health Institute (Basel, Switzerland).

2.7 Analysis

The analysis of all data was performed on log-transformed data on growth (i.e. number of cells counted after 48 hrs in the black box). All experiments were tested with an ANOVA using the statistical package JMP (SAS 2003). Significant results are presented with p-values followed by asterisks (* for $p < 0.05$; ** for $p < 0.01$; *** for $p < 0.001$; **** for $p < 0.0001$).

3 Results

3.1 Experiment 1a

When separated by quartz, only tester populations related to the repetition of the experiment (Table 1). The inducer populations had a negative effect on mean growth in tester populations (Table 1) (confer also Fig. 4 in Fels 2009). There was no correlation between the two populations neither across all experiments (ANOVA: degree of freedom = 1; sum of squares = 0.462; F ratio = 1.444; $p > F = <0.245$) nor within experiments (ANOVA: degree of freedom = 1; sum of squares = 0.0001; F ratio = 0.003; $p > F = <0.961$). Note, cell populations without neighbours (i.e. control populations) were significantly related to the repetition of the experiment (ANOVA: degree of freedom = 4; sum of squares = 6.719; F ratio = 52.471; $p > F = <0.0001$****).

Table 1 This table shows for experiments 1a and 1b both, relations between cell growth in the outer, the tester population (TP) and the inner, the inducer population (IP) as well as growth relations of TP and IP with the environment (env) due to repeating the experiments (RE) (ANOVA; *df* degrees of freedom; *SS* sum of squares)

Experiment	Relation of IP with env due to RE	Relation between IP and TP	Relation of TP with env due to RE
1a (quartz)	$p = 0.231$	$p = 0.008$**,[a]	$p < 0.0001$****
	($df = 4$; SS $= 0.308$; $F = 1.577$)	($df = 1$; SS $= 0.386$; $F = 7.865$)	($df = 4$; SS $= 5.366$; $F = 23.520$)
1b (glass)	$p = 0.038$*	$p = 0.571$[b]	$p = 0.0031$**
	($df = 4$; SS $= 1.154$; $F = 3.333$)	($df = 1$; SS $= 0.027$; $F = 0.328$)	($df = 4$; SS $= 3.328$; $F = 6.486$)

[a] IP had decreasing effect on cell growth in TP (confer Fig. 4 in Fels 2009)

[b] Neither group had a decreasing effect on the other (confer Fig. 4 in Fels 2009)

3.2 Experiment 1b

When separated by glass, inducer and tester populations did not impose effects on each other's growth but related both to the repetition of the experiment (Table 1). The two populations were positively correlated across (ANOVA: degree of freedom $= 1$; sum of squares $= 3.515$; F ratio $= 36.389$; $p > F = < 0.0001$****) as well as within experiments (ANOVA: degree of freedom $= 1$; sum of squares $= 0.841$; F ratio $= 10.868$; $p > F = <0.0053$**) (confer also Fig. 5 in Fels 2009). Note, cell populations without neighbours (i.e. control populations) were significantly related to the repetition of the experiment (ANOVA: degree of freedom $= 4$; sum of squares $= 63.967$; F ratio $= 23.313$; $p > F = < 0.0001$****).

3.3 Experiment 2

Only tester populations stood under the effect of repeating the experiment (Table 2). A negative correlation was found between the two populations taking all measurements together and remained significant when only taking the means per repetition (Fig. 2; Table 3). Within experiments correlations were—except for one case—not found between growths of the two populations (statistics not shown). Performing the experiment on two locations (Paris and Basel) contributed significantly to cell growth (see Fig. 2) but otherwise was corrected for (confer Tables 2, 3).

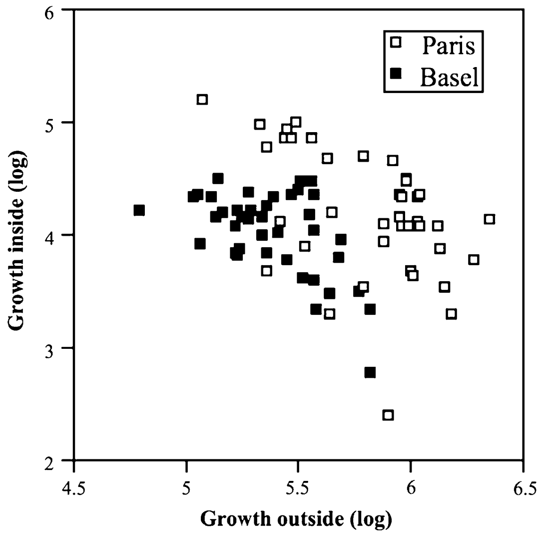
4 Discussion

This study on mutually exposed cell populations finds a pattern of cell-to-cell and cell-to-environment relation strikingly resembling the pattern of particle-to-particle and particle-to-measurement (environment) relation performed by quanta in typical

Table 2 This table refers to experiment 2 and shows the relation of the inducer (IP) and tester populations (TP) with repeating the experiment (RE) corrected for the contribution of the co-variable location (ANOVA; *df* degrees of freedom, *SS* sum of squares)

Population	Factor	*df*	SS	*F* ratio	$p < F$
TP	RE	1	2.931	35.144	<0.0001****
	Location	1	3.697	50.335	<0.0001****
IP	RE	1	0.208	0.875	0.352
	Location	1	0.590	2.53	0.116

Fig. 2 This figure refers to experiment 2. The *x* axis shows cell growth in the outer cuvette [referred to as inducer populations (IP)]. The *y* axis shows cell growth in the inner cuvette (referred to as tester populations (TP)). The *upper graph* refers to all measurements, the *lower graph* to the means of the (7) experiments (for statistics confer Tables 2 and 3). Note that IP and TP are negatively related



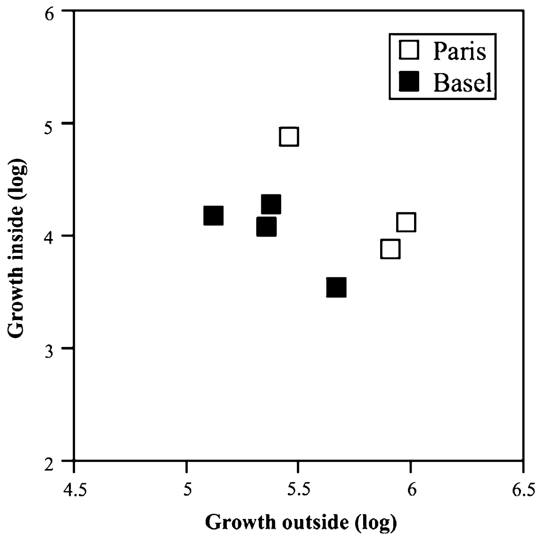


Table 3 This table refers to experiment 2 and shows growth relations between outer (IP) and inner populations (TP) taking all (79) measurements or only the means (7) of each experiment (ANOVA; *df* degrees of freedom; *SS* sum of squares). Effects are corrected for contributions from the co-variable location (Paris and Basel, see Fig. 2)

Data from	Factor	*df*	SS	*F* ratio	$p < F$
All measurements	IP-TP relation	1	4.679	26.789	<0.0001****
	Location	1	3.831	21.933	<0.0001****
Means of experiments	IP-TP relation	1	0.681	13.714	0.021*
	Location	1	0.677	13.64	0.021*

two-quanta entanglement experiments. This confirmed the working hypothesis of an a posteriori analysis, namely that relational patterns might be the same across system levels. Regarding these relational patterns we refer in the following to cells of the biological system of *Paramecium caudatum* (Ciliata), a unicellular aquatic organism.

Before discussing this relational pattern in detail we refer to the controls. When these singly kept cell populations were repeatedly growing for 2 days in darkness, they didn't do so independently but rather in relation with an (unknown) environmental factor. One may speculate here that the cells cannot grow independently, that "they have to tune in with an environmental factor". It reminds one of Kozlov's experiments (2000) where singly kept cell populations grew according to background radiation. However, while Kozlov (2000) varied experimentally the cell-perception of this background radiation (by shielding it), we are faced in this study with an unknown (but assumingly varying) factor and future studies only will allow determining it. To summarize the observation we can, nevertheless, interpret *sensu* the working hypothesis that singly kept populations had one degree of freedom (*df*) to relate with the environment and they did so. Whether cells need to relate with the environment will remain until further studies an open question. However, interestingly, in one experiment (1b, with populations separated by normal glass) both groups related with the environment (leading automatically—i.e. without using a *df* for it—to a correlation between them) and neither of them had a decreasing (or increasing) effect on cell growth in the other group. However, we cannot *sensu strictu* distinguish whether both groups used their one degree of freedom relating with the environment (therefore passively correlating) or whether one followed growths efforts in the other group leading passively to a correlation with the environment. Looking now at those populations that related with each other, we refer again to the working hypothesis: Two populations have two degrees of freedom to relate with, while only one is needed per relation. Hence, knowing they do relate, one *df* is left and could be used for a relation with the environment, a relation, which was indeed found and as assumed performed by one of the groups only. Or, looking at it from the other side, namely regarding the cell-to-environment relation, there can only be one *df* involved for this relation and hence, one *df* is left and can be used establishing a cell-to-cell relation, which indeed was found. A closer look at the cell-to-cell relation shows us, e.g. for experiment 1a (confer also Fig. 4 in Fels 2009 where you can compare with the control population) that the (originally) five neighbouring cells had a decreasing effect on cell growth in their (originally) 25 neighbours and it was these latter that related to the environment. This decreasing effect is (however, peculiar it may appear to us) an established relation from one population to the other. Experiment 2 can be seen similarly, namely that the more one population grows the more it will impose a decreasing effect on the other, leading to the negative correlation between the populations when looked at over all experiments. However, the question is which population imposed this effect on the other (*sensu* the working hypothesis only one is needed for it). We can only indirectly say that the originally bigger population (referred to as inducer population) had that decreasing effect on the originally smaller population (referred to as tester population) for the latter was giving its *df* for relating with the environment. Note that suppressing another population means, no matter what the other does its level of expression is just suppressed. It is, hence, no contradiction that one population can relate with the environment while the suppressing one is not automatically related with the environment as well.

Comparing now the relational pattern for those experiments where one population related with the other with the description of a typical entanglement result with two quanta, we find the following similarities: One observable relates to an external factor (repetition of experiment or measurement, respectively) and the other relates (causally or non-causally) to the first one. The occurrence of that pattern of relations, however, has implications. One is its support regarding the basic assumption of generalized quantum theory, namely that laws of nature might be true across system levels (rather than within only). Even though it was unclear to the author on what grounds he could have predicted which part of the pattern the individual group would establish, he believes that a repetition of these experiments would lead to the same results, because they themselves represent a regularity. Thus, (at least until we know better) an uncertainty about the outcome of a new type of experiment would always exist beforehand but some predictions can be made anyway. In an arrangement of two mutually exposed populations of cells (e.g., *Paramecium caudatum*) either both relate with the environment but then they do not relate with each other (but see above), or they relate with each other but then one of them will relate with the environment.

Coming back to the obtained results there appears the question of what is stabilizing this pattern across the repetitions of the experiments: In other words, why aren't group A and group B in a stochastic external and internal relation, respectively? One rather reductionist answer would be that one of the groups determines (for reasons we do not know) the relation; repeating the experiment that group would again determine the relation and finally we would get the observed pattern. Another perspective would be to assume that the pattern itself is also an observable, meaning that the regularity in the use of the two degrees of freedom of the two groups of cells is the expression of an additional use of a degree of freedom, namely one that comes from the system itself and does not organise cell division but the relational pattern of the two groups. A side conclusion from this would be to interpret emergence as resulting from such a system's degree of freedom to organize subsystems into non-predictable patterns (Morowitz 2002). Let us put this speculation for a moment further. When two groups relate with each other they express three degrees of freedom, two from themselves and one from the system they build. Again, that third degree of freedom would then (i) organise the regularity in the behaviour of the groups, having in addition (ii) the particular characteristic of being non-local. Interestingly, this brings us to complementarity, because the two groups (subsystems) building up their system form a complementary structure of system and subsystems, where none is the other nor would it be without the other. Taking this together with the assumed characteristic of the (above-mentioned) system's degree of freedom we find a striking resemblance with the postulation … *that non-local correlations* (i.e. entanglement) *and complementarity of observables can be understood as properties intrinsic to all kinds of systems* (von Stillfried and Walach 2006). However, before calling the relational patterns that are described in this study, a result of entanglement (or regarding higher system levels generalized entanglement) one needs to understand how subgroups contribute to the relational pattern and, therefore, remains for the time being on firm grounds keeping the formula in its (simpler) form, namely that two relating groups use two degrees of freedom to organize the relation. This simpler form still demands to understand (i) what the external factors are and (ii) what determines which group relates to that factor.

In conclusion, cells appear as being constrained to relate at least with the environment. When groups of cells are close enough to relate with each other and will do so, one group still establishes a relation with the environment. Thinking of embryology where cells differentiate into interrelated types of cells one might speculate that this increasing number of types (groups) started from simple relational patterns as described here. Interestingly, when we think of a multi-cellular organism's information processing regarding its integration in its ecosystem, we find sensory cells that relate with an external signal (e.g. smell, optical cue, or temperature) and nervous cells that relate with these sensory cells. At the single cell level, however, signals will be transmitted from molecule to molecule thus reaching the world of quantum mechanics (confer in this context McFadden 2000). Within ecosystems there are even more levels of organization (from photons to molecules, cells and organs, organism, group members, and species communities). These levels are assumed to display (i) the same principles (see introduction, von Stillfried 2010) and (ii)—as it was given evidence for in this study regarding cell-to-cell relation—the same relational patterns.

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References

Ananthaswamy A (2003) Entangled photons dance across the blue Danube. NewSci, p 15

SAS (2003) JMP statistics and graphics guide (Version 5.0.1.2). SAS Institute, CARY

Aspect A, Dalibard J, Roger G (1982) Experimental test of bell's inequalities using time-varying analyzers. Phys Rev Lett 49:1804–1807

Atmanspacher H, Römer H, Walach H (2002) Weak quantum theory: complementarity and entanglement in physics and beyond. Found Phys 32:379–406

Fels D (2005) The effect of food on microparasite transmission in the waterflea *Daphnia magna*. Oikos 109:360–366

Fels D (2009) Cellular communication through light. PLoS One 4:e5086

Fels D, Kaltz O (2006) Temperature-dependent transmission and latency of *Holospora undulata*, a micronucleus-specific parasite of the ciliate *Paramecium caudatum*. Proc R Soc B 273:1031–1038

Julsgaard B, Kozhekin A, Polzik ES (2001) Experimental long-lived entanglement of two macroscopic objects. Nature 413:400–403

Kozlov AA (2000) The role of natural radiation background in triggering cell division. In: Beloussov L, Popp F-A, Voeikov V, van Wijk R (eds) Biophotonics and coherent systems. Moscow University Press, Moscow, pp 241–248

Mcfadden J (2000) Quantum evolution. Flamingo, London

Morowitz HJ (2002) The emergence of everything. How the World became complex, 1st edn. Oxford University Press, Oxford

Von Lucadou W, Römer H, Walach H (2007) Synchronistic phenomena as entanglement correlations in generalized quantum theory. J Conscious Stud 14:50–74

Von Stillfried N (2010) Theoretical and empirical explorations of “generalized quantum theory”. In *Kulturwissenschaftliche Fakultät*, Vol Ph.D. pp 236. Europa-Universität Viadrina, Frankfurt an der Oder

Von Stillfried N, Walach H (2006) The whole and its parts: are complementarity and non-locality intrinsic to closed systems? Int J Comput Anticip Syst 17:137–146

Wichtermann R (1986) The biology of paramecium, 2nd edn. Plenum, New York